

# SYSTEMATIC ERRORS IN OPERATIONAL NATIONAL METEOROLOGICAL CENTER PRIMITIVE-EQUATION SURFACE PROGNOSSES

COLLEEN LEARY

Massachusetts Institute of Technology, Cambridge, Mass.

## ABSTRACT

This paper describes an attempt to find systematic errors in the sea-level forecasts produced by the operational six layer primitive-equation model of the National Meteorological Center, Suitland, Md. The sample of cases studied contains 417 storms from the winter of 1969-1970. Several systematic errors exist. Over the oceans, the model does not forecast storms deep enough. Storms forming on the lee slopes of the Rocky Mountains are forecast too deep and too warm. Storms fill more slowly and deepen more rapidly than the model predicts. Strongly deepening cyclones move to the left of the forecast track.

## 1. INTRODUCTION

The NMC (National Meteorological Center) six layer PE (primitive-equation) forecasting model (Shuman and Hovermale 1968) has, as one of its products, a forecast of sea-level pressure and thickness of the layer between 1000 and 500 mb. This paper describes an attempt to find systematic errors in the model's forecasts of storms by comparing the 36-hr surface prognostic charts produced by the six-layer model to the patterns that actually occur.

## 2. STORMS

The sample includes storms from November and December 1969 and January and February 1970, using all days having both forecast and verification charts available. The forecast charts verify at 1200 GMT, 36 hr after the initial time when the forecast is made. These verification charts and 36-hr forecast charts, as received by facsimile, contain labeled contours of pressure (at 8-mb intervals) and thickness (at 60-m intervals). For obtaining a manageable sample size and for keeping the cases somewhat independent of one another, we did not include in the sample any forecasts verifying at 0000 GMT. This condition introduces the possibility that results obtained from this sample contain a bias because of the diurnal uniformity of the forecasts.

Cases chosen for the sample possess a closed cyclonic circulation (i.e., they have one or more closed isobars on either the forecast or the verification chart). Both charts need not have a closed isobar. The designations "not forecast" and "not observed" describe cases where no obvious center of circulation exists in a region where one is observed or forecast, respectively. Storms labeled "not forecast" always show the model's failure to predict pressures low enough at the center of the storm. Storms labeled "not observed" always represent forecasts of too low pressures. In all, the data include 417 storms, with information about the forecast, the verification, and (when available) the initial time of the forecast, 36 hr before verification. For a few storms that do not have charts for the initial time and for which accurate interpolation is possible, the initial data come from 12 hr before and after the initial time.

The data obtained for each forecast, verification, and initial state of a storm include:

1. The latitude and longitude of the center of circulation.
2. The central pressure of the storm.
3. The thickness at the center of circulation.
4. The type of storm.

The machine that plots the forecast chart cannot plot an arbitrarily small closed isobar. This introduces a discrepancy between the forecast charts and the hand-plotted verification charts on which much smaller closed isobars appear. The sizes of the smallest closed isobars indicated by the curve plotter are found by looking for the smallest closed isobars on months of forecast charts. On the hand-plotted charts, isobars smaller than these limiting isobars are ignored and from here on are assumed not to exist. The center of circulation is the geometric center of the isobar of lowest pressure in the storm. The central pressure is the labeled value of the isobar of lowest pressure in the storm.

Each storm belongs to one of seven types: (1) lee side cyclone, (2) frontal wave, (3) wave cyclone, (4) occluding cyclone, (5) occluded cyclone, (6) cold Low, and (7) old cold Low. This grouping represents a progression from the youngest to the oldest storms and the increasing penetration with age of the sea-level Low into the strong thickness gradient. A storm belongs to the group with characteristics that it most closely resembles. These characteristics are:

1. Lee side cyclone—relative age, 1; cyclogenesis on the lee side of a mountain range; sea-level Low on a thickness ridge.
2. Frontal wave—relative age, 1; thickness gradient behind the sea-level Low; thickness pattern with little distortion; only one or two closed isobars associated with the sea-level Low.
3. Wave cyclone—relative age, 2; sea-level Low near the edge of the strong thickness gradient; thickness pattern somewhat convoluted; cyclone deepening.
4. Occluding cyclone—relative age, 3; sea-level Low penetrating the thickness pattern toward colder air; comma-shaped distortion of the thickness pattern; cyclone deepening.
5. Occluded cyclone—relative age, 4; sea-level Low on cold side of the strong thickness gradient; comma-shaped distortion of the thickness pattern.
6. Cold Low—relative age, 5; sea-level Low near or over the coldest air; Low separated from strong thickness gradient; Low filling or of constant central pressure.
7. Old cold Low—relative age, 6; Low center over coldest air; Low dissociated from strong thickness gradient; Low filling.

The 417 storms in the sample range in position from longitude 30°W westward to 150°E and from latitude 20°N to 80°N, approximately the boundaries of the area covered by the forecast and verification charts. Reasons for not using most storms beyond and some near the boundaries include difficulty in reading the charts in regions near the Pole, not enough of the Low on the chart to determine its center, and inability to decide whether a forecast (verification) is not verified (forecast) or just located off the chart. Stationary Low centers over northern Mexico are ignored because they might be artificially introduced by the process of reducing pressure to sea level in that region.

### 3. ERRORS IN FORECASTING PRESSURE

In this paper, error is always the forecast value minus the observed value. For central pressure, a positive error means that the forecast storm is not as deep as the observed storm. A negative error means that the forecast is too deep. Errors in forecasting the central pressure of sea-level cyclones show systematic variations according to the positions of the observed storms. The pattern of errors emerges when the errors in central pressure of the storms

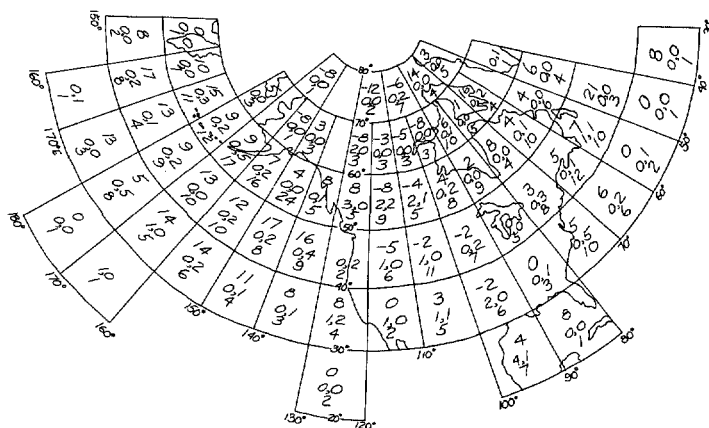


FIGURE 1.—Area-averaged errors in pressure; top number, averaged error of storms occurring in the block (in millibars); second row, number of storms not observed and number of storms not forecast; bottom number, total number of storms belonging in the block.

in the sample are plotted at the observed positions of the storms and averaged over blocks of area. In figure 1, the blocks have sides of 10° longitude and 10° latitude, except between 70° and 80°N where the blocks have sides of 20° longitude and 10° latitude. Storms lying on the boundaries between two blocks belong to the block in which they will lie on the east edge or the south edge. The top number in each block is the average error in central pressure (in millibars) over the storms in the block having a numerical error. Below this comes the number of storms forecast but not observed followed by the number of storms observed but not forecast. These two types of storms are not included in the averaging. The last number in the block is the total number of storms included in the block.

Over the oceans, the averaged error is positive, corresponding to a strong tendency for the model to produce forecasts that are not deep enough. Over parts of the North American Continent, particularly on the east side of the Rocky Mountains where lee side cyclones often occur, the error is negative (i.e., in this area, the PE model forecasts the storms too deep). Over the United States east of the Mississippi River, the error is positive but small or zero. This area lies between the region of negative error and the Atlantic Ocean's region of large positive error. In this middling region, errors are not especially large for storms that the model predicts, but the model is "ignorant" of many storms that occur along the East Coast.

Errors in forecasting the central pressure of sea-level Lows also depend on the type of Low observed. Table 1 breaks down the sample by type of storm and error in central pressure. Over half (56%) of the lee side cyclones and 41 percent of the frontal waves are forecast too deep. In the other, older types of storms, only between 6 and 14 percent are forecast too deep. The pattern of errors reverses with Lows not forecast deep enough. Only 12 percent of the lee side cyclones and 21 percent of the frontal waves have positive errors. Occluded cyclones have the most (79%). Occluding cyclones, cold Lows, and old cold Lows all strongly favor positive errors. Wave cyclones are most likely to be missed entirely in the forecasts, and lee side cyclones and old cold Lows are least likely not to be forecast. In contrast, lee side cyclones (26%) and frontal waves (33%) are the only types for which unverified forecasts of Low centers present a problem. Among the other

TABLE 1.—Cases sorted by type of storm and error in central pressure; error is forecast value minus observed value; the numbers in parentheses indicate percent

Error in central pressure	Type of storm						
	Lee side cyclone	Frontal wave	Wave cyclone	Occluding cyclone	Occluded cyclone	Cold Low	Old cold Low
Not observed	13 ( 26)	8 ( 33)	2 ( 3)		1 ( 2)		
−16	1 ( 2)					1 ( 1)	1 ( 2)
−8	14 ( 28)	2 ( 8)	7 (11)	6 ( 6)	4 ( 8)	6 ( 8)	3 ( 6)
0	16 ( 32)	9 ( 38)	13 (21)	20 ( 18)	6 ( 12)	18 (25)	14 ( 29)
+8	3 ( 6)	1 ( 4)	16 (26)	31 ( 28)	16 ( 31)	24 (33)	19 ( 39)
+16			3 ( 5)	18 ( 17)	12 ( 23)	10 (14)	7 ( 14)
+24				10 ( 9)	4 ( 8)	1 ( 1)	1 ( 2)
+32				3 ( 3)	2 ( 4)	1 ( 1)	
Not forecast	3 ( 6)	4 ( 17)	20 (33)	21 ( 19)	7 ( 13)	11 (15)	4 ( 8)
Total	50 (100)	24 (100)	61 (99)	109 (100)	52 (101)	72 (98)	49 (100)

TABLE 2.—Cases sorted by forecast deepening rate and observed deepening rate (both in mb/36 hr); minus signs indicate filling.

Observed deepening rate	Forecast deepening rate						
	-24	-16	-8	0	+8	+16	+24
-32			1				
-24	3	1	2				
-16	4	4	4				
-8	2	16	14	4			
0	2	9	23	25	6		
+8		3	11	22	8		
+16				11	5	2	1
+24			1	4	2	4	
+32				2	2	2	
+40							
+48							1
Median observed deepening rate	-16	-8	0	+8	+8	+24	+16
Average observed deepening rate	-14	-7	-2	+7	+11	+27	+16

five types, only three cases are forecast but not observed. The depth of young storms is systematically overforecast, and the intensity of older storms is systematically underforecast.

Comparing the forecast deepening rate to the observed deepening rate gives another view of the errors in central pressure. Forecast deepening rate means the difference between the central pressure of the Low center at the initial time and the forecast central pressure. Observed deepening rate means the difference between the central pressure of the Low center at the initial time and the verified central pressure. For both types of deepening rate, a positive sign indicates a deepening storm; and a negative sign indicates a filling storm. Table 2 shows a breakdown of all 190 cases having deepening rates into categories depending on the combination of forecast deepening rate and observed deepening rate. This table shows that, on an average, the forecast deepening rate is less than the observed deepening rate. Thus, storms deepen faster and fill more slowly than the model predicts. Relatively few storms (9%) deepen more slowly or fill more rapidly than the model predicts.

#### 4. ERRORS IN FORECASTING THICKNESS

Errors in thickness are tabulated both because the forecast thickness pattern is a product of the PE model and because thickness, as a measure of temperature, relates to physical effects that might cause systematic errors in the forecasts of sea-level pressure. The thickness errors of the storms in the sample show some pattern when sorted geographically, by type of storm, and when compared with errors in central pressure. As with other quantities, the error in thickness is the forecast value minus the observed value. A positive thickness error means that the forecast is too warm. A negative thickness error means that the forecast is too cold. Geographically, the negative thickness errors (forecasts too cold) favor the oceanic areas, and the positive thickness errors (forecasts too warm) favor the North American Continent. Overall, positive errors predominate. In figure 2, the thickness errors for the storms in figure 1 (except those not forecast and those not observed) are averaged over the same

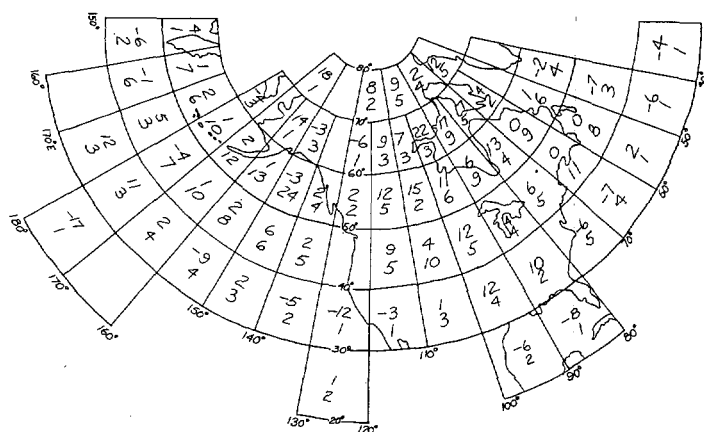


FIGURE 2.—Area-averaged errors in thickness (see also fig. 1); top number, averaged error of storms occurring in the block (in tens of meters); bottom number, total number of storms averaged in the block.

TABLE 3.—Thickness errors averaged by type of storm; error is forecast value minus observed value; units of thickness, tens of meters; the numbers in parentheses indicate percent.

Type of storm	Average of all thickness errors	Range of errors	No. of storms with thickness error			
			>0	<0	=0	Total
Lee side cyclone	+7	-9 +26	27 (79)	6 (18)	1 (3)	34 (100)
Frontal wave	-4	-19 +24	4 (33)	8 (67)		12 (100)
Wave cyclone	+2	-20 +23	19 (49)	18 (41)	4 (10)	39 (100)
Occluding cyclone	+3	-24 +36	50 (57)	30 (34)	8 (9)	88 (100)
Occluded cyclone	+2	-14 +21	23 (53)	19 (44)	1 (2)	43 (99)
Cold Low	+2	-13 +18	26 (43)	26 (43)	8 (13)	60 (99)
Old cold Low	+6	-7 +48	32 (71)	9 (20)	4 (9)	45 (100)

latitude and longitude blocks and are plotted along with the number of storms averaged in a given block. The pattern resembles the pattern of errors in central pressure, especially the difference in sign between ocean and continent. Over the Atlantic Ocean, the regions of negative thickness error roughly follow the Gulf Stream.

Table 3 shows the thickness errors related to type of storm. On an average, frontal waves are forecast too cold by 40 m, and all other types are forecast too warm. Lee side cyclones have the greatest positive error, with an average of 70 m too warm. Old cold Lows also have a large positive average error of 60 m. The other types of storms are on an average too warm by 20 or 30 m. The wide range of thickness error in any single category casts doubt on the validity of the averages as comparisons between categories. Confidence in the averages, however, is restored by their close relationship to the numbers of storms with positive, negative, and zero errors, as shown in table 3.

Table 4 shows similar data for storms categorized by the error of the forecast in predicting the central pressure of the storms. As the error in central pressure increases from most negative to most positive, the error in thickness decreases from most positive to most negative; or, the storms forecast too cold tend to be forecast not deep enough. The storms forecast too deep are mostly forecast too warm. These averages, as before, reflect the number of

TABLE 4.—Thickness errors averaged by error in central pressure; error is forecast value minus observed value; units of thickness, tens of meters; the numbers in parentheses indicate percent.

Error in central pressure	Average of all thickness errors	Range of errors	No. of storms with thickness error			
			>0	<0	=0	Total
-16	+9	+1 +17	3 (100)			3 (100)
-8	+8	-10 +32	32 (76)	7 (17)	3 (7)	42 (100)
0	+3	-19 +39	52 (55)	33 (35)	10 (11)	95 (101)
+8	+2	+20 +48	58 (53)	41 (37)	11 (10)	110 (100)
+16	+1	-24 +18	28 (56)	21 (42)	1 (2)	50 (100)
+24	-1	-16 +21	6 (40)	9 (60)		15 (100)
+32	-2	-17 +21	2 (33)	3 (50)	1 (17)	6 (100)

storms in each category forecast too warm and forecast too cold. Here also, the range in each category shows that extreme errors in both directions occur without respect to the average error in thickness.

### 5. ERRORS IN FORECASTING POSITION

According to a rule by Rosenbloom (1969); the developing sea-level Low moves to the left of the forecast track. Testing this rule for the 36-hr forecasts produced by the six-layer model involves a sample of 35 storms. Each of these storms deepens 16 mb or more over the forecast period and has well-defined positions at the initial, forecast, and verification times. Only 35 storms from the total of 417 fulfill these conditions. Plotting the initial position on a map and drawing lines connecting it with the forecast and observed positions (also plotted) determines whether the observed track is to the left of, to the right of, or along the forecast track. Of the 35 storms, 23 (66%) move to the left of the forecast track, 8 (23%) move to the right of the forecast track, and 4 (11%) move along the forecast track. This 66-percent agreement with Rosenbloom's rule shows that the six-layer model based on the primitive equations exhibits a tendency toward the same kind of error in forecasting tracks of sea-level Lows that Rosenbloom (1969) claims for much less elegant forecasting techniques.

In figure 3, the 323 storms having both forecast and observed positions are grouped according to the direction of the observed storm relative to the forecast storm. The nine possible directions showing the possible errors in position are (1) northeast, (2) northwest, (3) southeast, (4) southwest, (5) north with no error in longitude, (6) south with no error in longitude, (7) east with no error in latitude, (8) west with no error in latitude, and (9) right on (identical forecast and observed positions). There exists a tendency for storms to occur east of the forecast position. Of the total, 55 percent have this error while 38 percent of the storms occur west of the forecast position and 7 percent have no error in longitude. More storms occur north of the forecast than to the south, but the difference (48% compared to 41 percent) is small; 11 percent of the storms have no error in latitude. The most popular location of observed storms is northeast of the forecast (27%). Southeast (21%) and northwest (20%) follow in the number of storms with these errors. Of the four quadrants, storms least frequently occur

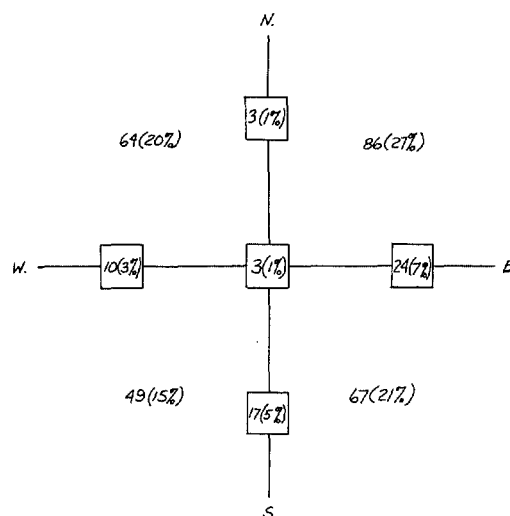


FIGURE 3.—Positions of observed storms relative to positions of forecast storms.

(15%) southwest of the forecasts. Under the assumption that storms, on an average, follow northeastward tracks, these data support a systematic slowness along such tracks in the PE model's forecasts.

### 6. EXAMPLES OF FORECASTING ERRORS

One example of the typical overforecasting of cyclone depth on the lee slopes of the Rocky Mountains by the PE model occurs on the forecast verifying at 1200 GMT on Nov. 21, 1969. The forecast for that verification time shows a storm with a central pressure of 992 mb at the position 55°N, 117°W; it sits on the top of a thickness ridge and has a central thickness of 5470 m. The Low actually observed at the verification time has a 1008-mb central pressure, with the 1008-mb contour unclosed. Figure 4 compares the forecast and the verification. The storm occurs at 55°N as forecast, but at 110°W (7° east of the forecast) and farther from the mountains. The thickness ridge also occurs east of the forecast and has considerably less amplitude than the forecast. In shape, the forecast warm ridge shows more character than the weaker observed ridge, in the form of a pronounced northwest to southeast tilt. The forecast thickness of 5470 m differs from the observed thickness of 5300 m by 170 m. The observed Low sits to the west of the thickness ridge, so the large error in forecasting the storm too warm comes from both the overestimate of the amplitude of the warm ridge and the underestimate of the distance of the sea-level Low from the warm ridge.

An example of the PE model's inability to forecast oceanic storms deep enough occurs on the forecast for Jan. 25, 1970. The forecast storm at latitude 46°N and longitude 47°W has a central pressure of 1000 mb, with the 1000-mb contour unclosed. The forecast Low center has a thickness of 5300 m and lies between the thickness trough and the thickness ridge. At verification time, the real storm has a closed contour of 976 mb for the central pressure, 24 mb deeper than the forecast, centered at

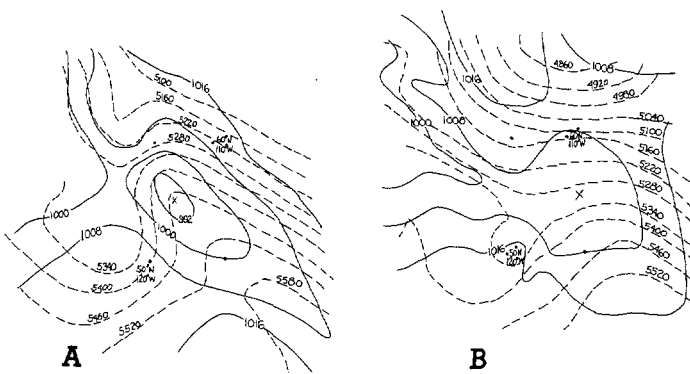


FIGURE 4.—Forecast and verification of a lee side cyclone on Nov. 21, 1969, at 1200 GMT; (A) 36 hr PE surface prognosis and (B) surface pressure and 1000- to 500-mb thickness.

47°N, 46°W. The observed Low lies on top of the thickness ridge, which is also much more intense than forecast. The observed central thickness is 5460 m, 160 m warmer than the forecast. The observed thickness ridge also has a northwest to southeast tilt and shows suggestions of a comma-shaped structure (fig. 5). This description of the errors in forecasting an oceanic occluding cyclone is the reverse of the discussion of the lee side cyclone. The forecast of the lee side cyclone mirrors the observed oceanic cyclone, and the forecast over the ocean resembles the observation over land.

## 7. DISCUSSION

Over land, particularly near the Rocky Mountains, differences in methods used by the PE model and observing stations to obtain sea-level pressures may account for some systematic negative error in pressure.

The smoothed topography of the PE model may cause an underestimate of friction, a force which acts to inhibit the development of storms. An underestimate of the strength of the frictional mechanism is also consistent with forecasts too deep over land, especially near mountains.

Another physical effect the PE model takes into account is sensible heat, released when cold air passes over warmer water. As noted in section 4, the pattern of negative thickness errors over the Atlantic Ocean follows the Gulf Stream. Also, the warm North Equatorial Current flows into the Gulf of Mexico, another region of too cold forecasts. In the Pacific Ocean, areas of negative average-thickness error lie along still another warm current, the North Pacific Current. Two remaining regions of negative error occur in the Gulf of Alaska and off the coast of Siberia, regions where cold continental air streams over the warmer ocean water in winter. The sensible heating mechanism in the PE model, if strengthened and applied with greater resolution, could act to warm the forecasts in

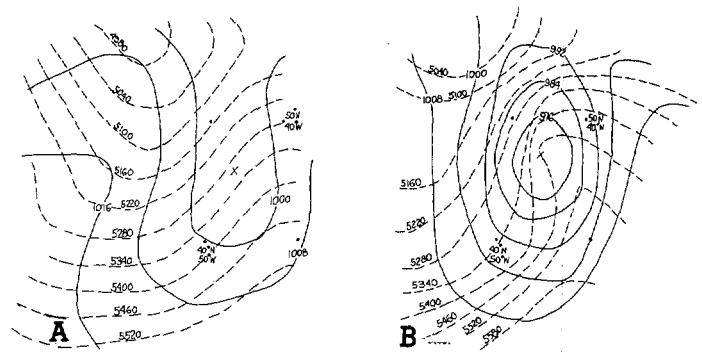


FIGURE 5.—Forecast and verification of an oceanic occluding cyclone on Jan. 25, 1970, at 1200 GMT; (A) 36 hr PE surface prognosis and (B) surface pressure and 1000- to 500-mb thickness.

regions where they are too cold now. In table 4, negative errors in thickness are related to positive errors in pressure. Increasing the contribution of sensible heat could result in greater depth of intensifying cyclones over the oceans and also increase the amplitude of the thickness ridge.

## 8. CONCLUSIONS

The NMC surface forecasts produced by the six layer PE model show several systematic errors. The depth of oceanic cyclones is generally underforecast. The depth of cyclones forming on the lee slopes of the Rocky Mountains is generally overforecast. Forecasts, on the average, underestimate the deepening rate and overestimate the filling rate of storms. Most forecasts of thickness over land are too warm. Many forecasts of thickness over the oceans are too cold. There exists a tendency for storms to occur north and east of the forecast position. Strongly deepening cyclones tend to obey Rosenbloom's rule (1969) and move to the left of the forecast track.

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